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Ultra-precision grinding of ceramics with injection moulded tools

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Abstract
From piezoceramic sensors to dental implants, ceramics are used in a wide range of applications due to their paramount mechanical, thermal and electrical properties. Ultra-precision grinding is one of the typical machining processes used to achieve a high form accuracy and surface quality in these hard and brittle materials, when considering the critical undeformed chip thickness. The grinding tool is a critical element in ultra-precision grinding. Usually, soft bonded tools with diamond grit in the micrometre range (d << 100 µm) are used. The scope of this paper is to investigate the grinding performance of a novel, injection moulded grinding tool with a polypropylene (PP) bonding system in comparison with a resin bonded tool having the same grit size and concentration (D7, C25) for machining carbide ceramics (SiC). A detailed investigation was carried out to analyse the achievable surface roughness, form accuracy, tool wear and process forces for surface grinding in a five axis ultra-precision machine tool. Due to the softer bonding system in injection moulded grinding tools (ca. 75 N/mm^2 hardness compared to ca. 200 N/mm^2 in resin bonded tools), surface roughness of less than 20 nm can be achieved at higher material removal rates compared to conventional resin bonded tools. However, the tool wear in injection moulded tools is up to 1.5 times higher.

Ultra-precision grinding, ceramics, grinding tools, soft bonding system

1. Introduction

The machining of hard and brittle materials by micro grinding enables the production and thus the use of wear and chemical resistant materials for micro parts and components. This manufacturing process offers significant advantages for applications ranging from biomedicine [1] to replication moulds [2,3]. Replication moulds made of brittle material such as silicon carbide (SiC) are state of the art in the manufacturing of high quality optics by glass moulding, since only ceramic materials are able to resist the elevated temperatures, high pressures and chemical loads governing the replication process of glass [3-5]. High shape accuracy and low surface roughness are critical factors in order to manufacture high quality lenses [3,4,6]. This poses a challenge to the production of ceramic moulds, since low roughnesses require a defect free surface [7]. Hence the use of ultra-precision grinding is required as a well-established process for manufacturing moulds that fulfil the low surface roughness and shape accuracy requirements for glass moulding tools [8]. In this study, ultra-precision grinding experiments are carried out with injection moulded grinding tools in order to investigate the grinding performance of this novel, soft bonding system in the machining of polycrystalline SiC.

2. Ultra-precision grinding

Surface grinding experiments were carried out using a five axes ultra-precision machine tool (Nanotech 500 Freeform Generator). The tool metrology system is attached to the machine's frame next to the workpiece spindle, in order to provide an in-situ tool profile assessment (cf. Figure 1). The grinding tools applied are conventional, resin bonded, spherical grinding pins as well as injection moulded (polymer bonded) grinding tools, the latter consisting of a compound of fine iron powder (d = 2 µm) and diamond grit embedded in a polymer matrix of polypropylene (PP).

Both bonding systems were used to machine polycrystalline silicon carbide workpieces (CVD-SiC).

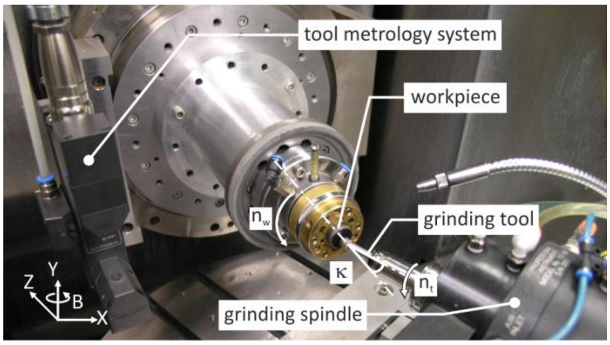

Figure 1. Experimental grinding set-up with in-situ tool metrology.

2.1. Grinding and Dressing Conditions

The surface grinding experiments were conducted based on a full factorial variation of tool type, depth-of-cut and feed velocity in order to analyse the surface grinding process at different specific material removal rates and compare the achievable surface quality and wear of injection moulded grinding tools with conventional, resin bonded ones. Dressing and grinding parameters are shown in Table 1.

2.2. Measurement and Analysis

For shape measurements, a laser interferometer (Mesa H010, Zygo Corp.) with a measuring field of 150 mm in diameter was used. The maximum peak-to-valley data (PV) over the workpiece's cross-section was used as the measure for overall shape accuracy. The surface roughness was assessed by a white light interferometer (Talysurf CCI HD) with a measuring field of 820 x 820 µm^2. The arithmetic mean surface height Sa is used as roughness parameter for further analysis based on the S-L surface (S filter = 0.08 µm, L filter = 80 µm).

A laser metrology system (BLUM LaserControl Nano NT) was used to measure the tool wear *in situ* by assessing the tools' profile up to an angle of 88 degrees and determine the deviation from a nominal tool profile.

Table 1. Dressing and grinding conditions.

Dressing Parameters	
Dresser rotation speed n_d	3 000 min^{-1}
Tool rotational speed n_t	3 000 min^{-1}
Grinding Parameters	
Tool inclination angle κ	20° / 30° / 40°
Grinding spindle rotat. speed n_t	11 500 to 22 700 min^{-1}
Workpiece rotational speed n_w	178 min^{-1}
Cutting speed v_c	2.44 m/s
Depth of cut a_e	0.5 / 1 / 3 µm
Feed velocity v_f	0.5 / 1 / 3 µm
Number of passes	20 / 10 / 4
Coolant	Paraffin (MQL)
Workpiece material	CVD-SiC polycristalline
Workpiece hardness	2 500 HV
Average grain size (workpiece)	5 µm

3. Results and Discussion

The investigation aims to identify favourable parameter sets to achieve low surface roughness and high shape accuracy while minimizing tool wear. The diagrams (cf. Figures 2 and 3) depict the variation of depth-of-cut and feed velocity determined over the specific material removal rate Q'_w in 10^{-3} mm^3/mms.

3.1. Surface Roughness and Shape Accuracy

Being one of the most critical quality criteria in the manufacturing of optical moulds, the surface roughness, here expressed as the arithmetical mean surface roughness Sa, was determined for all parameter sets as depicted in Figure 2. Low material removal rates and the softer bonding system (polymer) have a positive influence in the surface roughness. The shape deviation lies under 2 µm for all experiments and can therefore be considered low. However, the lower grit concentration of the polymer bonded grinding tools in combination with the polymer's low hardness (max. 75 N/mm^2) leads to lower shape accuracy.

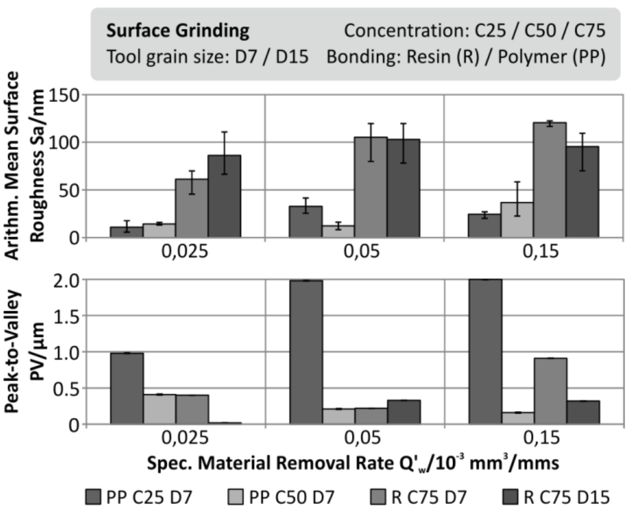

Figure 2. Surface roughness (Sa) and shape accuracy (PV) of ground plano surfaces in CVD-SiC using soft bonding systems.

3.2. Tool Wear

The profile of all grinding tools was assessed before and after grinding experiments, in order to obtain the radial difference between the profiles and determine the tool wear. Figure 3 depicts the trend of a higher tool wear in the softer, polymeric bonding system.

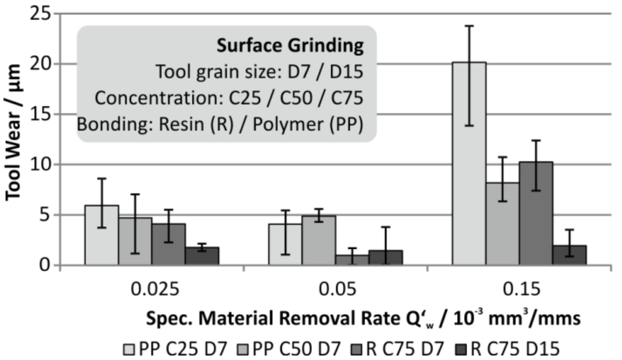

Figure 3. Tool wear of resin and polymer bonding systems after surface grinding of CVD-SiC.

4. Conclusions and Outlook

Ultra-precision grinding experiments were carried out using an injection moulded grinding tool with a polymeric bonding system to machine plano surfaces in CVD-SiC workipeces. In order to compare the grinding performance of the polymer bonding to similar, conventional grinding tools, a resin bonding system was incorporated into the experiments.

Due to the softer, polymeric bonding system of the injection moulded grinding tools, it is possible to achieve an optical surface quality (Sa of ca. 10 nm), which is a main requirement for many optical applications, such as for glass moulding tools. High shape accuracy (PV better than 0.2 µm), as it is the case in the higher grit concentration (C50), is also achievable and in some cases lower than the shape accuracy obtained with resin bonded tools (ca. 0.4 µm in average).

Additional research will focus on the wear mechanisms of the polymeric bonding system and its performance in oxide ceramics (e.g. alumina and zirconia). By analysing the tool wear *in situ*, it is possible to compensate the tool wear during grinding, thus improving the workpieces' shape accuracy.

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